

Prepared in cooperation with the U.S. Fish and Wildlife Service and the Joint Water Commission

# **Evaluation of Restoration Alternatives Using Hydraulic Models of Lake Outflow at Wapato Lake National Wildlife Refuge, Northwestern Oregon**

Scientific Investigations Report 2020-5014

U.S. Department of the Interior  
U.S. Geological Survey

**Cover:** Wapato Lake in winter when lake has been inundated with rainwater, northwestern Oregon.  
Photograph by Stewart Rounds, U.S. Geological Survey, March 1, 2020.

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DAVID BERNHARDT, Secretary

**U.S. Geological Survey**  
James F. Reilly II, Director

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## Conversion Factors

U.S. customary units to International System of Units

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
<b>Length</b>		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
<b>Area</b>		
acre	4,047	square meter (m <sup>2</sup> )
acre	0.4047	hectare (ha)
<b>Volume</b>		
acre-foot (acre-ft)	1,233	cubic meter (m <sup>3</sup> )
<b>Flow rate</b>		
cubic foot per second (ft <sup>3</sup> /s)	0.02832	cubic meter per second (m <sup>3</sup> /s)

International System of Units to U.S. customary units

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
<b>Length</b>		
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
<b>Area</b>		
hectare (ha)	2.471	acre
<b>Volume</b>		
cubic meter (m <sup>3</sup> )	35.31	cubic foot (ft <sup>3</sup> )
cubic meter (m <sup>3</sup> )	0.0008107	acre-foot (acre-ft)
<b>Flow rate</b>		
cubic meter per second (m <sup>3</sup> /s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m <sup>3</sup> /s)	35.31	cubic foot per second (ft <sup>3</sup> /s)

## Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

## Abbreviations

DEM	digital elevation model
DSS	data storage system
GIS	geographic information system
HEC-RAS	Hydrologic Engineering Center-River Analysis System
lidar	light detection and ranging
NWR	National Wildlife Refuge
OWRD	Oregon Water Resources Department
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WMST	Water Management Scenario Tool

# Evaluation of Restoration Alternatives Using Hydraulic Models of Lake Outflow at Wapato Lake National Wildlife Refuge, Northwestern Oregon

By Stewart A. Rounds<sup>1</sup>, Stephen L. Pilson<sup>2</sup>, Annett B. Sullivan<sup>1</sup>, and Adam J. Stonewall<sup>1</sup>

## Abstract

Wapato Lake National Wildlife Refuge near the city of Gaston in northwestern Oregon was established in 2013, and planning is underway to restore a more natural lake and wetland system after more than 100 years of agricultural activity on the lakebed. Several water-management and restoration alternatives are under consideration, one of which involves opening and reconnecting Wapato Lake's outlet to allow flow in and out of the lake to Wapato Creek and downstream to the Tualatin River. The effects of this and other alternatives are being evaluated, partly through a detailed examination of the lake's water budget. The water budget for the lake during 2011–13 was quantified by the U.S. Geological Survey in partnership with U.S. Fish and Wildlife Service and others. Results were incorporated in a spreadsheet-based Water Management Scenario Tool (WMST) for Wapato Lake, which predicts the effects of various management actions on daily lake level and potential habitat areas for waterfowl or other target species. Incorporating the effects of a hypothetical open outlet between the lake and the downstream river network in the WMST was accomplished by using a hydraulic model to simulate the flow-exchange rate between Wapato Lake and Wapato Creek over a wide range of lake levels and downstream river conditions. A Hydraulic Engineering Center-River Analysis System (HEC-RAS) one-dimensional unsteady flow model was constructed and calibrated for Wapato Creek and part of the Tualatin River using data from October 2011 to April 2013, and then was used to simulate daily lake/creek exchange flows in water years 1992–2014 under hypothetically constant lake levels. Results were used to populate a table of lake/creek flow-exchange rates for use in the WMST; a dynamic link between the WMST and HEC-RAS was unrealistic because it would require hundreds of subroutine calls to HEC-RAS and result in long run times for a single water-year's WMST calculations with daily time steps. Predictions of daily outlet flows from the WMST were checked against HEC-RAS simulated flows under daily varying lake levels to

ensure that the timing and magnitude of lake/creek exchange flows used by the WMST were consistent with those of the hydraulic model. Two scenarios were tested with a hypothetical open lake outlet to show how the WMST could be used to inform restoration planning—one scenario used a year-round open lake outlet, and the other scenario closed that outlet for part of the high-water winter season. Results showed that flows in and out of a year-round open lake outlet would dominate the lake's water budget and produce water depths during winter and through mid-summer that might be too deep to support waterbird species that require shallow water. Closing the lake outlet during large winter storms and high-water conditions in the downstream river network would isolate the lake from surrounding rivers, keep the lake level lower, and retain substantially more shallow-water areas. Because of the ease with which management alternatives can be evaluated, a water-budget spreadsheet tool such as the WMST has been a valuable part of an analysis of potential water-management and restoration alternatives for Wapato Lake National Wildlife Refuge.

## Introduction

National wildlife refuges have complex ecosystems with continuously changing interactions among wildlife, vegetation, hydrology, and climate. This complexity can make it difficult to predict the effects of potential management scenarios. Models often are used by decision makers to estimate the effects of management options prior to carrying out expensive or time-consuming restoration activities. Models that include and accurately represent the most important processes that respond to potential management options and are driven by reliable data are the most likely to produce reliable information for decision making. Once a model is built and calibrated to represent processes occurring at a specific location, it becomes a tool that can be used to examine a wide range of situations.

In this study, a hydraulic model of two river reaches downstream of Wapato Lake in northwestern Oregon was constructed and calibrated and its results were incorporated in

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<sup>2</sup>U.S. Fish and Wildlife Service

an existing water-budget spreadsheet tool to assist in evaluating management options for the recently established Wapato Lake National Wildlife Refuge (NWR). Wapato Lake is surrounded by levees and external canals that route tributaries around the lake and allow the lakebed to be farmed in summer. The hydrology of the system is tightly controlled, with no open-flow connections to streams outside the lakebed and water export controlled by pumping. Refuge managers are considering various options to manage the newly created refuge. One option includes the establishment of a more-natural flow connection between the lake and Wapato Creek, which flows downstream to the Tualatin River (U.S. Fish and Wildlife Service, 2019). This natural connection could provide many benefits; however, much uncertainty exists with regard to how an open-flow connection could affect the lake and downstream rivers.

A range of scenarios for restoration of Wapato Lake has been considered with an existing water management tool developed by the U.S. Geological Survey (USGS)—the Wapato Lake Water Management Scenario Tool (WMST; Rounds and others, 2020). The WMST is a water-budget spreadsheet tool that uses a daily water budget to predict lake water levels, depths, volumes, and potential habitat areas under various management options. The daily water budget includes inputs such as precipitation, tributary inflows, groundwater discharge, and leakage through levees and the pumphouse; and water losses such as evapotranspiration, open-water evaporation, groundwater recharge, and pumping. Management options available for analysis in the WMST include the simulation of pumping and outflow weirs, tributary removal or addition, and imposition of a range of hydrologic and meteorological conditions to gain insights into historical or future water availability and habitat. One critical limitation of the original WMST is that it could not estimate the flow exchange through a hypothetical open connection between Wapato Lake and Wapato Creek.

## Purpose and Scope

The goals of this study were to construct and use a hydraulic model to (1) estimate the flow exchange through an open downstream outlet at the north end of Wapato Lake, and (2) incorporate those results in a daily water budget for Wapato Lake so that restoration and water-management strategies could be evaluated. The hydraulic model includes a section of the Tualatin River and Wapato Creek from its mouth to Wapato Lake, and was developed using the U.S. Army Corps of Engineers Hydrologic Engineering Center-River Analysis System (HEC-RAS). For this study, a HEC-RAS unsteady flow model was calibrated and verified for conditions that occurred during 2011–2013, and then was used to predict water levels and flows in Wapato Creek at the outlet of Wapato Lake under a range of hydrologic conditions. This report describes (1) construction and calibration of the HEC-RAS model to simulate flow conditions that occurred during

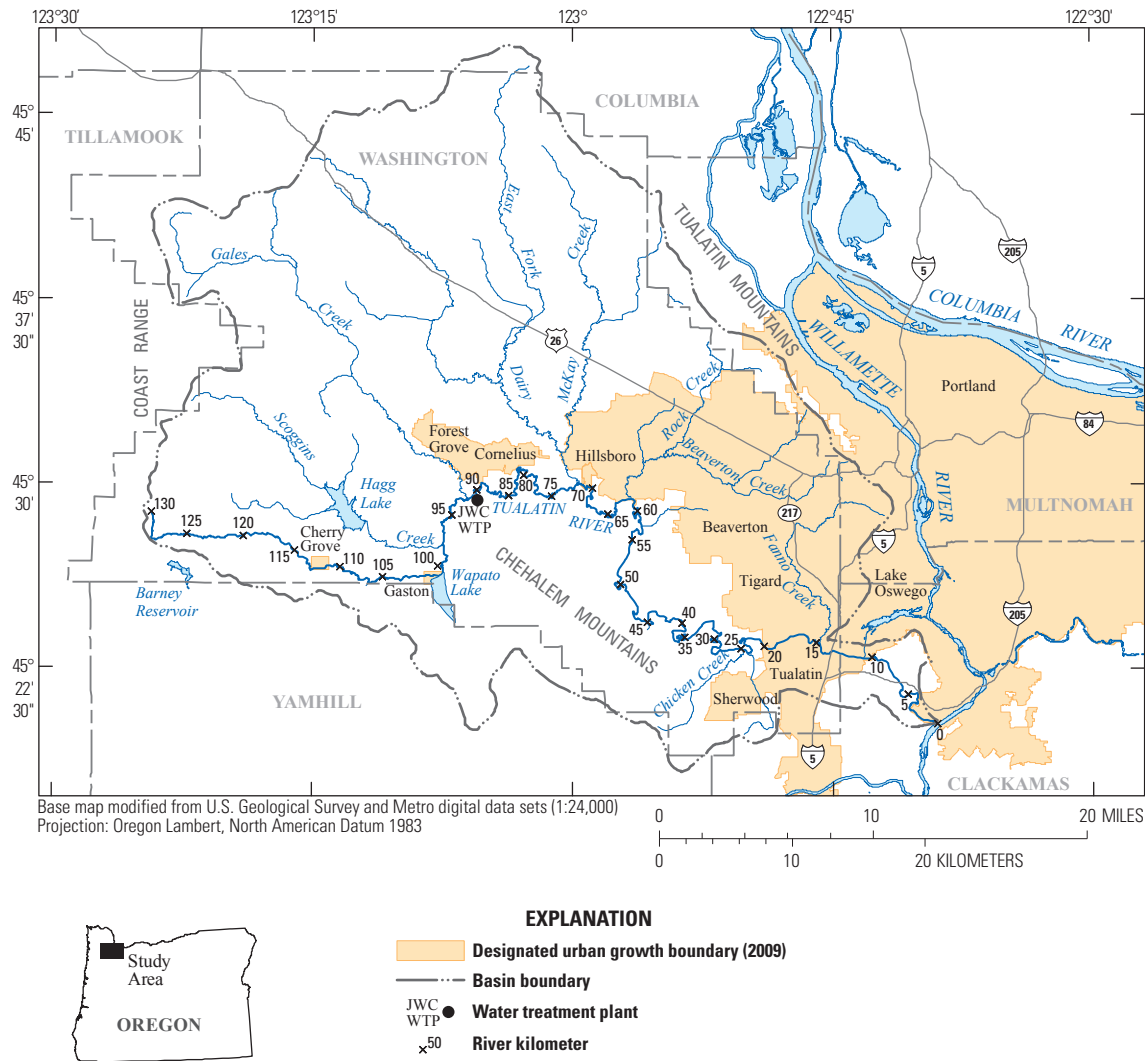
water years 1992–2014; (2) integration of HEC-RAS model results in the WMST for an open-outlet condition; and (3) results from sample water-management scenarios for Wapato Lake using an open lake outlet to evaluate the potential effects on lake level and water depth, with ramifications on potential habitat for target species.

## Study Site

Wapato Lake is a 320-hectare (790-acre) shallow lake located in the Tualatin River Basin near the city of Gaston in northwestern Oregon (figs. 1–2). Historically, the lake received flows from several tributary creeks as well as reverse flows from the nearby Tualatin River and Wapato Creek during winter high-water conditions (Washington County, 1872). Beginning in 1895, canals were constructed in and around the lake to drain it each spring for farming. By the 1930s, 8.9 km (5.5 mi) of levees had been constructed around the lakebed and its tributaries had been routed to canals outside the levees to decrease the lake's water inputs. In addition, a pump station had been constructed at the northern end of the lake to make the lake easier to empty (Cass and Miner, 1993). In a typical year, rainwater and groundwater seepage would accumulate in the lake in autumn and winter, which then would be pumped out in spring to provide dry land for agriculture. Years of exposing lakebed soils to the atmosphere caused peat deposits to decompose and the lakebed to subside by as much as 1.5–2.1 m (5–7 ft; Christy, 2015), with the implication that the lake could be substantially deeper now than it was in the 1800s. The lake's history, soils, topography, and water budget are described in more detail by Rounds and others (2020).

In 2007, after a series of land acquisitions from willing sellers, the U.S. Fish and Wildlife Service (USFWS) established Wapato Lake as a unit of the Tualatin River National Wildlife Refuge. Wapato Lake historically was an important site supporting waterfowl in northwestern Oregon, and has great potential for the restoration of its lacustrine, wetland, and riparian systems (U.S. Fish and Wildlife Service, 2007). In 2013, the Wapato Lake Unit was converted to the Wapato Lake National Wildlife Refuge as the 562nd refuge in the National Wildlife Refuge System. USFWS thereafter began planning for future restoration of native systems to support migrating and wintering waterfowl, raptors, songbirds, fish, amphibians, and reptiles, among other fauna. Among many alternatives under consideration is an option to restore an open-flow channel at the northern end of Wapato Lake (its historical outlet) to connect the lake to Wapato Creek and farther downstream to the Tualatin River (fig. 3; U.S. Fish and Wildlife Service, 2019). An open-flow connection could simplify water management at the refuge, restore a more-natural condition to nearby rivers, and eliminate the operation and maintenance costs of pumping.

Restoration of an open lake outlet, however, would introduce additional management issues. During periods when Tualatin River flows are high, such as during winter



**Figure 1.** Tualatin River Basin, including Wapato Lake in the southwestern part of the basin, near Gaston, northwestern Oregon. JWC, Joint Water Commission; WTP, water treatment plant.

storms, reverse flow conditions can occur in Wapato Creek; an open connection between Wapato Lake and Wapato Creek could allow large volumes of river water to enter the lake and greatly increase the lake level. At certain times of year, high water levels in Wapato Lake may be undesirable, as most of the lake could be too deep to provide habitat for some waterbird species. Numerous studies have concluded that water depth is an important factor linking the abundance and foraging success of waterbirds (Bancroft and others, 2002; Bolduc and Afton, 2008; Lantz and others, 2011), and that relatively shallow water (<0.25 m [ $<0.82$  ft]) is selected by many species of shorebirds, wading birds, and dabbling ducks, whereas deeper water is preferred by other species such as diving ducks (Fredrickson, 1991; Murkin and others, 1997; Elphick and Oring, 1998; Colwell and Taft, 2000; Taft and others, 2002). An open lake outlet also may allow the introduction of various fish species into the lake, including steelhead trout (*Oncorhynchus mykiss*) listed as threatened under

the Endangered Species Act of 1973 (Public Law 93–205, 87 Stat. 884, as amended), which in turn might require the development of plans to manage common carp (*Cyprinus carpio*) or prevent the stranding of steelhead when water levels recede in summer (U.S. Fish and Wildlife Service, 2019). In addition, rapid changes in lake level could disrupt plant and wildlife communities (Fredrickson, 1991). If poor water-quality conditions were to develop in the lake, an open lake outlet could allow that water to be exported and create water-quality problems downstream. Indeed, the export of poor-quality water from Wapato Lake occurred in the summer of 2008 in conjunction with an algal bloom in the lake, with detrimental downstream effects on municipal-water treatment and recreational uses (Rounds and others, 2015). Therefore, it is important to understand the details of an open connection between Wapato Lake and Wapato Creek when considering alternatives for restoration planning, including the conditions when the connection would be active, when reverse flow



**Figure 2.** Wapato Lake when the lake was refilling with rainwater, northwestern Oregon, winter 2015. Photograph by Stewart Rounds, U.S. Geological Survey, January 27, 2015.



**Figure 3.** Wapato Creek looking north (downstream) from the Gaston Road bridge at the northern tip of Wapato Lake, northwestern Oregon, 2010. Photograph by Stewart Rounds, U.S. Geological Survey, July 21, 2010.

conditions could occur, and the magnitude of exchange-flow rates. Such information is critical to the water budget of the lake and prediction of lake levels and water-depth areas tied to potential habitat conditions.

In evaluating a restoration scenario that includes an open lake outlet, refuge managers will need to predict and understand lake conditions and availability of target-species habitats that may result from a free-flowing connection between Wapato Lake and Wapato Creek. With an open connection, the lake has the potential to become deep (more than 2 m [6.6 ft])

at times, which might limit its value to certain guilds of water-birds such as dabbling ducks. Simulating an open lake outlet with a calibrated hydraulic model and incorporating the results in a detailed lake water budget allows managers to evaluate the water levels and water-depth fluctuations that might occur if the lake were connected to the creek without any kind of control structure.

## Methods

### Overview

To model an open lake outlet in the existing Wapato Lake WMST, it was first necessary to develop a dynamic flow model of Wapato Creek and part of the Tualatin River using HEC-RAS version 4.1.0 (U.S. Army Corps of Engineers, 2010). HEC-RAS can simulate steady and unsteady (time-variant) streamflow in river channels and floodplains, including flow under bridges and through hydraulic structures. The model predicts water-surface elevation, velocity, and flow amount and direction at any point in the modeled reach. The model was calibrated, and then run iteratively under a range of river conditions and lake levels to develop a lookup table of exchange flows that the WMST could use to calculate the magnitude and direction of flow exchange between Wapato Lake and Wapato Creek. A dynamic dependence of WMST on the HEC-RAS model was not introduced because such a link would require the WMST to make subroutine calls to initiate a HEC-RAS model run for every daily time step of the water-budget calculations, resulting in unrealistically long run times for the calculations of a single water-year. To evaluate whether the simulation of exchange flows through an open outlet was accurately represented in the WMST, the WMST and the

HEC-RAS model were used to predict lake/creek exchange flows under identical conditions for a selection of representative water years (for example, dry, wet, and average rainfall). After evaluating the accuracy of WMST predictions, the WMST was used to predict lake levels as well as lake areas meeting target water-depth criteria under two example restoration scenarios.

## HEC-RAS Model Construction

### Geometry

The HEC-RAS model domain included 5.75 km (3.57 mi) of the Tualatin River from Gaston (Oregon Water Resources Department [OWRD] station 14202510) to Dilley (USGS station 14203500), and Wapato Creek from a point south of the bridge at Gaston Road (USGS station 14202630) to its confluence with the Tualatin River approximately 3 km (1.9 mi) downstream (fig. 4). HEC-RAS requires stream cross-sectional data throughout the model extent to characterize the channel and floodplain shape and to compute flow and water level at those locations. USFWS contracted with Minister-Glaeser, Inc. to survey cross sections along Wapato Creek from the Wapato Lake pumphouse (USGS station 14202630) to the creek's confluence with the Tualatin River. USGS staff surveyed cross sections in the Tualatin River channel from Gaston to Dilley. Data from in-channel surveys were blended with topographic data from a digital elevation model (DEM) derived from high-resolution light detection and ranging (lidar) data. Because the airborne lidar laser could not penetrate the water column, lidar data were valid only for the floodplain and in-channel surveys were needed to characterize the stream channels. In-channel data were blended with the lidar data by determining coincident channel-edge points and replacing invalid lidar-derived channel data with in-channel survey data. During this data-blending process, it became apparent that dense vegetation such as Himalayan blackberry (*Rubus armeniacus*) and reed canary grass (*Phalaris arundinacea*) had prevented the lidar laser from reaching ground level along the stream banks, causing the lidar dataset to have artificially high elevations at stream-channel edges; therefore, such elevations were decreased to better match the in-channel surveys. An ArcGIS™ extension, HEC-GeoRAS (U.S. Army Corps of Engineers, 2011), was used to generate the combined channel and floodplain cross-sectional geometries for the HEC-RAS model (fig. 5).

Survey measurements, photographic information, and field observations were used to characterize bridges and channel obstructions in the model. Two bridges and a beaver dam were modeled on Wapato Creek, and one bridge was modeled on the Tualatin River. The beaver dam was modeled as a “leaky” solid inline structure, allowing 0.014 m<sup>3</sup>/s (0.5 ft<sup>3</sup>/s) of flow to pass through when water elevation was below the crest of the structure. Manning's n roughness values were estimated

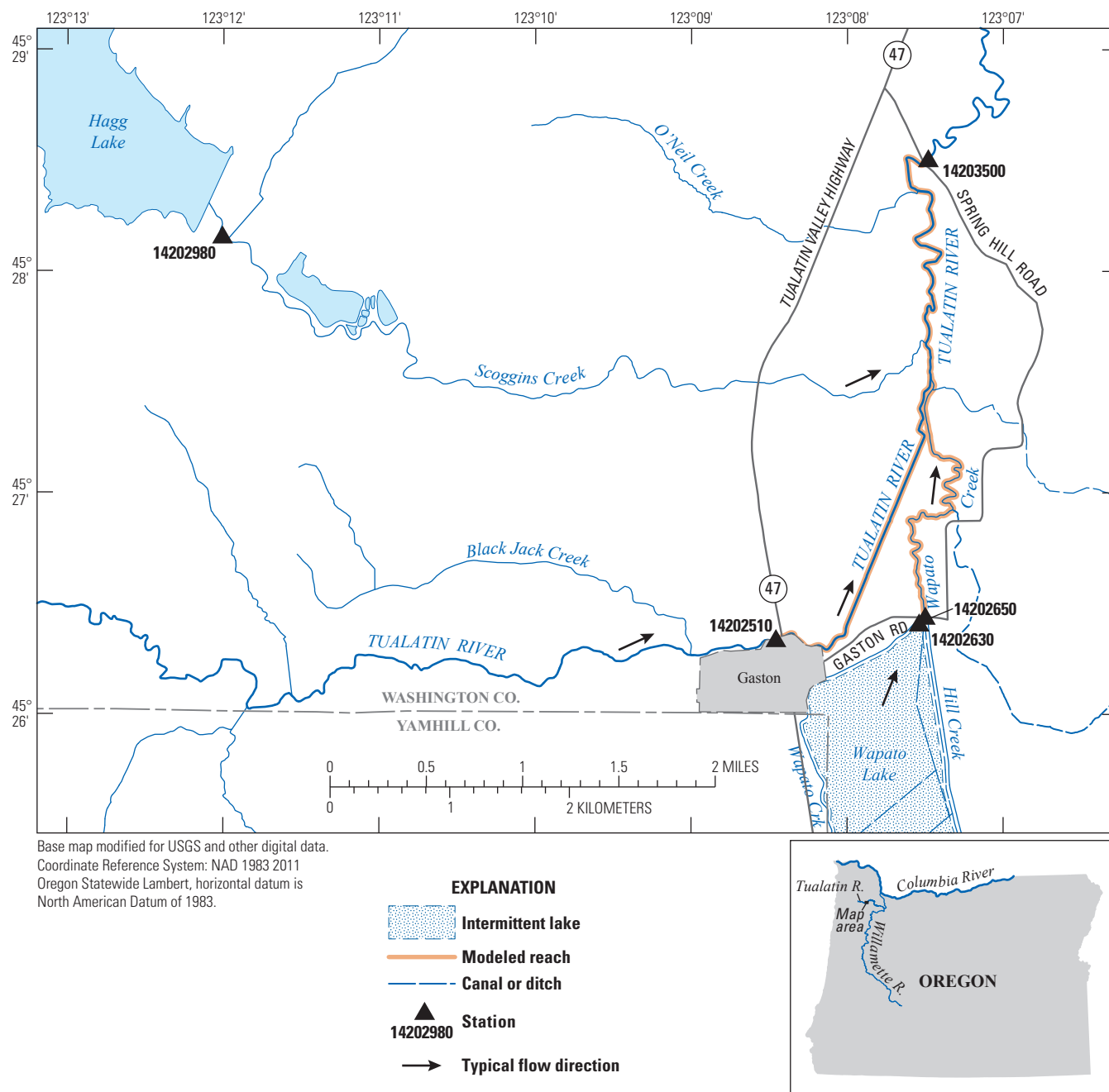
from a comparison of aerial and field photographs to values associated with a range of channel and vegetation types published in the scientific literature (Chow, 1959; Barnes, 1967). Ineffective flow areas were designated for overbank areas of cross sections where hydraulic connectivity to the main channel was unlikely for the modeled flow.

### Flow Data

For model calibration, flow boundary conditions were imposed for the upstream boundaries on the Tualatin River at Gaston (OWRD station 14202510), on Wapato Creek near Gaston Road (USGS station 14202650), and for the Scoggins Creek tributary (OWRD and USGS station 14202980; fig. 4). The downstream boundary on the Tualatin River at Dilley (USGS station 14203500) was modeled using a “normal depth” condition based on the friction slope of the channel so as not to constrain downstream elevations. The friction slope was computed in a geographic information system (GIS) by analyzing intervals between topographic contour lines generated from a 10-m DEM, with a result of  $1.1 \times 10^{-4}$ . Streamflow and water-surface elevation data were available from OWRD for the Tualatin River at Gaston (OWRD station 14202510), and from USGS for Wapato Creek at Gaston Road (USGS station 14202650). Scoggins Creek, a large tributary that joins the Tualatin River just downstream of the mouth of Wapato Creek, was included in the model as a lateral input, with streamflow data available from USGS, the Bureau of Reclamation, and OWRD at a site farther upstream (OWRD and USGS station 14202980). For calibration, streamflow and water-surface elevation data were available from USGS for the downstream boundary on the Tualatin River at Dilley (USGS station 14203500).

For initial construction and calibration of the model, 30-minute flow data for each location were stored in a data storage system (DSS) file to interface with HEC-RAS. The streamflow station on Wapato Creek at Gaston Road was operated only from October 2011 to April 2013, which limited the analysis window to that period for calibration and validation of the model. Because of overbank flows near Gaston during high-water conditions, OWRD did not publish Tualatin River streamflows greater than 18.4 m<sup>3</sup>/s (650 ft<sup>3</sup>/s) at OWRD station 14202510, which resulted in lengthy data gaps during winter. Missing data at OWRD station 14202510 were estimated using a water balance approach by subtracting flows measured at Scoggins Creek and Wapato Creek from those measured at Dilley. Because of slight variations in travel time and the presence of some runoff that was not accounted for in the water-balance method, small discontinuities sometimes occurred where the measured and estimated flows needed to be joined; the estimates were adjusted in such cases to ensure a seamless transition between the measured and estimated daily mean streamflows. Other smaller and intermittent data gaps in flow records were filled using simple linear interpolation.

## 6 Evaluation of Restoration Alternatives Using Hydraulic Models of Lake Outflow at Wapato Lake, Oregon

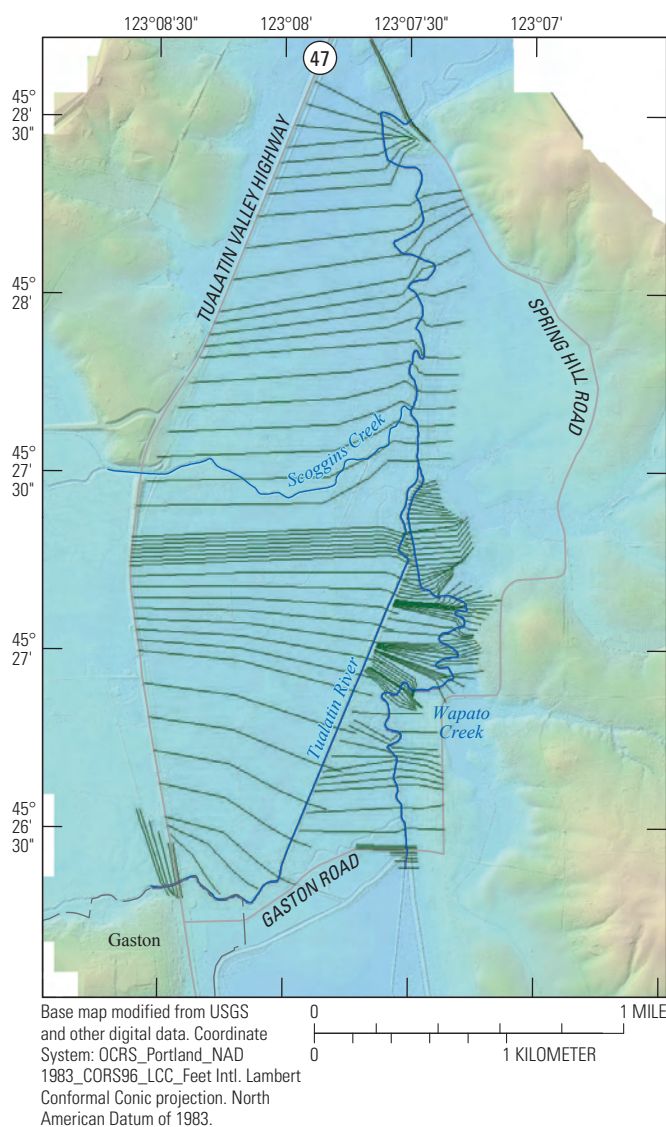


**Figure 4.** Study area showing the modeled reaches along the Tualatin River and Wapato Creek and nearby stations measuring streamflow and water level, near Gaston, northwestern Oregon.

### Lake/Creek Flow-Exchange Rates

After the HEC-RAS model was calibrated, daily flow-exchange rates through a hypothetical open connection between Wapato Lake and Wapato Creek were simulated over a wide range of conditions using hydrologic conditions that occurred during water years 1992–2014. To simulate these flow-exchange rates, measured flows were applied for Scoggins Creek and Tualatin River at Gaston inputs,

constant lake levels were imposed on the upstream boundary on Wapato Creek, and HEC-RAS simulated the downstream flows at Dilley using a normal-depth boundary condition. Each of the water years was simulated with a range of constant lake levels at the upstream boundary on Wapato Creek so that a lookup table could be produced for the WMST. The lookup table was simply a table of daily open-outlet flow-exchange rates as simulated by HEC-RAS, indexed by lake level and date (year and day of year), where date was a surrogate for



**Figure 5.** Modeled reaches of the Tualatin River and Wapato Creek, general topographic relief of the floodplain, and river cross sections included in the Hydrologic Engineering Center-River Analysis System (HEC-RAS) model of the Tualatin River and Wapato Creeks near Gaston, northwestern Oregon.

hydrologic conditions in downstream Tualatin River reaches that might constrain open-outlet flows due to backwater conditions.

The WMST calculates fluxes of various water-budget components on a daily time step. The calibrated HEC-RAS model, originally configured to run with 30-minute flow data for 2011–2013, was reconfigured to run with daily mean boundary conditions and for the longer 1992–2014 water-year period. Daily mean streamflow data for the Tualatin River at Gaston (OWRD station 14202510) were obtained from annual reports of the Tualatin River Flow Management Technical Committee (years 1992–2004; Oregon Water Resources Department, 1992–2004) and from OWRD (years

2005–2014; Oregon Water Resources Department, 2015a). Daily mean streamflow data for Scoggins Creek (OWRD and USGS station 14202980) were obtained from OWRD and USGS (Oregon Water Resources Department, 2015b; U.S. Geological Survey, 2015).

The WMST provides an option to impose hydrologic and meteorological conditions that are a precomputed percentile of the historical record. The HEC-RAS model, therefore, also had to be run with boundary conditions that represented the median, 10th, 25th, 75th, and 90th percentiles of streamflows in Scoggins Creek and the Tualatin River at Gaston. Percentiles of these daily mean streamflows were computed for each site by calculating the daily cumulative streamflow for each water year from 1992 to 2014, then computing the percentile for each day.

The model boundary condition at the upstream end of Wapato Creek, at Wapato Lake, was set to a constant lake level in each simulation. Twenty-three different lake elevations from 50.9 to 54.3 m (167 to 178 ft) were simulated at intervals of 0.15 m (0.5 ft) with separate model runs for each lake elevation, and applying the entire 1992–2014 water-year period for each lake level. Although a constant Wapato Lake elevation is unlikely to occur for any extended period, these constant-elevation model runs allowed HEC-RAS to generate a full range of Wapato Lake/Wapato Creek exchange flows under a wide range of lake levels and Tualatin River flow conditions. The model computed the magnitude and direction of daily streamflow along Wapato Creek in response to the imposed lake levels and downstream flow conditions. The lake/creek flow-exchange rates that were transferred to the WMST were taken from a location 3.18 km (1.98 mi) upstream of the mouth of Wapato Creek, at the upstream end of the Wapato Creek model domain.

## Open Outlet Addition to the WMST

An option to include an open connection between Wapato Lake and Wapato Creek was added to the WMST. This option essentially added another input or output to the lake's water budget, in which the daily flow-exchange rates were taken from a lookup table (based on HEC-RAS model results) in the WMST spreadsheet, using that day's lake level and date as indices to find the appropriate exchange rates in the lookup table and interpolate a result from the two nearest lake levels on that date. The date was a surrogate for the hydrologic and meteorological conditions that occurred at that time. Positive flow rates represent outflows from the lake, and negative flow rates represent inflows to the lake.

The outlet in the WMST can be open for certain date ranges specified by the user, and closed at other times. In this way, one can imagine a large gate at the lake outlet that could be closed under certain conditions. For example, the gate could be closed to prevent the lake from importing excessive amounts of water during periods of high-water conditions

downstream of the lake, or to prevent poor-quality water from being exported from the lake during an early summer algal bloom.

## Model Results and Evaluation of Water-Management Scenarios

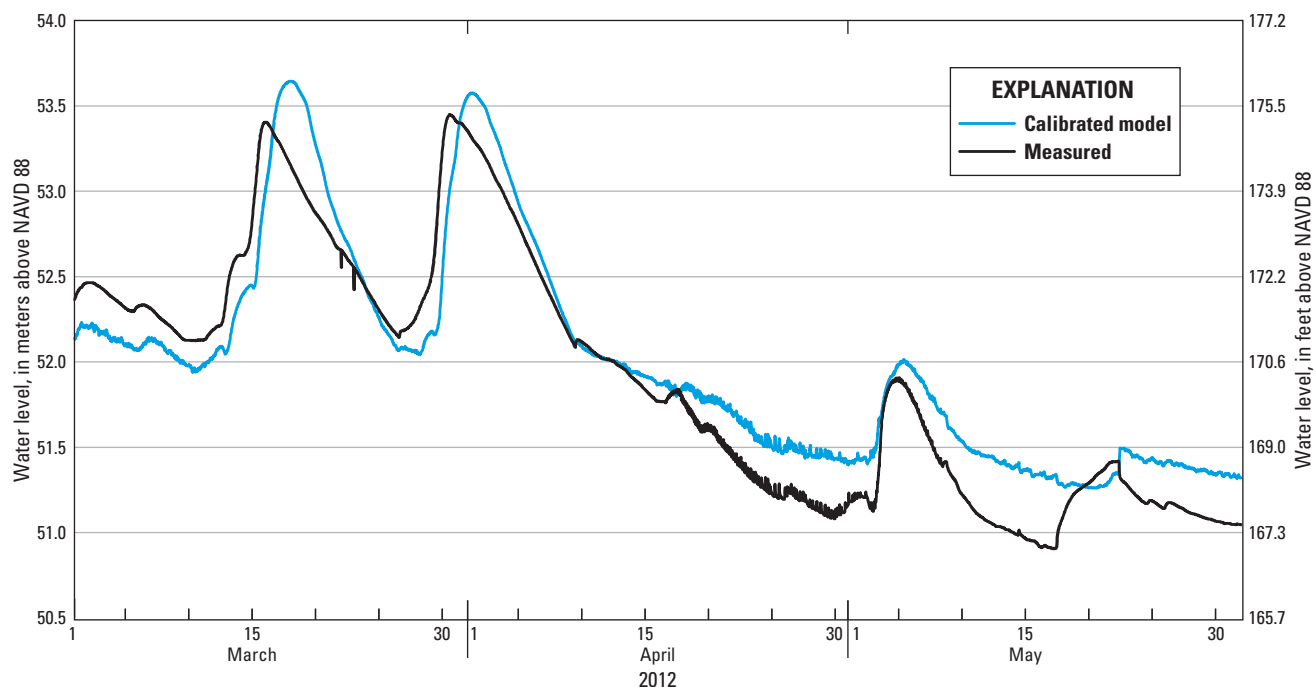
### HEC-RAS Model Calibration and Validation

Model calibration focused on a 3-month period during March–May 2012 that included high and low flows. Two March storms generated among the highest peak flows and water levels recorded at the Wapato Creek at Gaston Road site (USGS station 14202650) during the October 2011 to April 2013 period of record, followed by recession toward base-flow conditions in May 2012. Calibration consisted of adjusting model parameters until modeled water levels in Wapato Creek at Gaston Road produced the best comparison with measured water levels at that location. Several methods were used to optimize the model calibration, such as adjusting Manning’s *n* (roughness) values in the floodplain and stream channels, applying flow-based roughness factors to account for reduced friction during high flows, and using seasonal roughness factors to account for the presence or absence of vegetation.

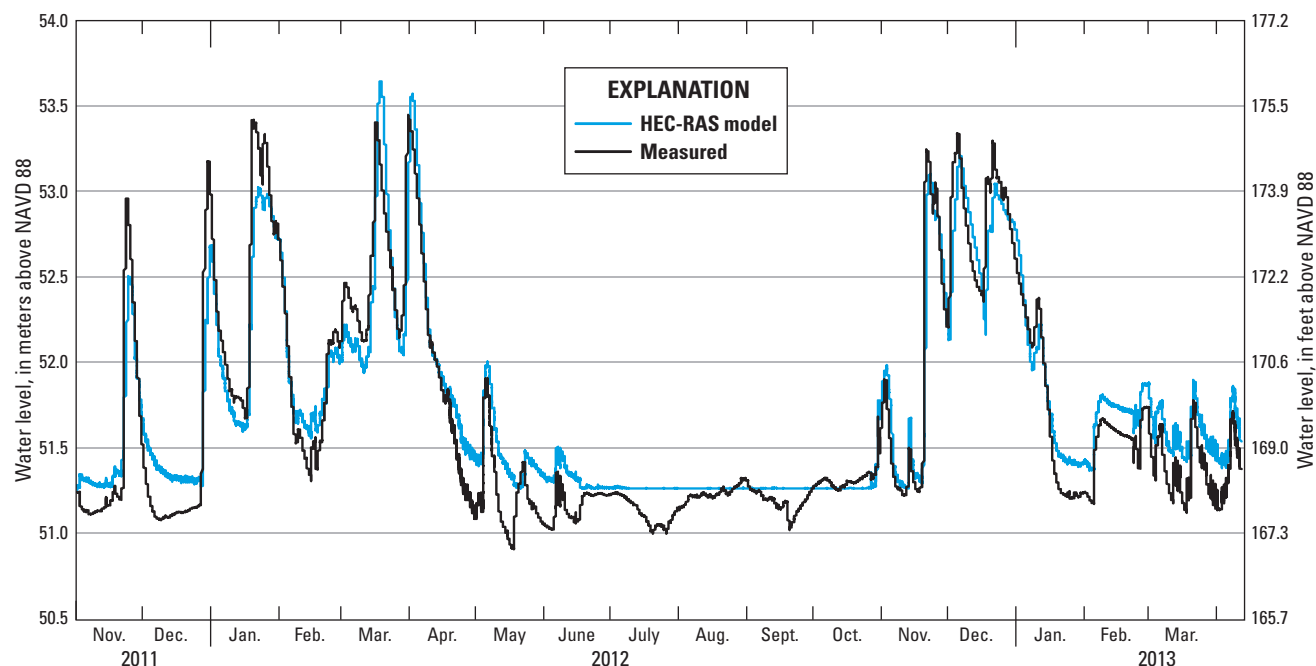
Calibration of the HEC-RAS model for March–May 2012 resulted in a fit to the measured water levels in Wapato Creek at Gaston Road that was deemed acceptable for this

application (fig. 6). Although the measured water level at that site varied as much as 2.55 m (8.35 ft) during that 3-month period, the mean absolute error (typical error) of the model was only 0.22 m (0.71 ft), with a mean error (bias) of 0.10 m (0.32 ft). The modeled water level matched almost all patterns in the data, rising and falling in response to storms at similar times and with similar magnitudes, with an exception in mid-to late-May when the measured water level increased on May 17, but the modeled water level showed no response (fig. 6). This discrepancy may have been caused by changes in pumping activity at the upstream Wapato Lake pump house, or by installation of flash boards in Wapato Creek downstream of the measurement site—activities that were not well documented and not included in the model. The measured water level also decreased during the last 10 days of April 2012 to a point that the model was not able to reproduce, perhaps because of uncertainties in the bathymetric data used to construct the model, and (or) because the model included a difficult-to-characterize beaver dam (a leaky weir) in Wapato Creek downstream of the measurement station. Varying the model’s roughness coefficients was not sufficient to retain a good fit for the peak water levels while also decreasing the baseline water level between storms.

Model performance was tested further, and somewhat independently, by comparing modeled and measured water levels for almost the full period of record of the Wapato Creek at Gaston Road station without further adjustment to the model calibration. For November 2011 to April 2013, the model reproduced the measured water levels even better than for the calibration period (fig. 7), with a mean absolute error of



**Figure 6.** Comparison of modeled and measured water levels in Wapato Creek at Gaston Road, northwestern Oregon (U.S. Geological Survey station 14202650), for the March–May 2012 calibration period. NAVD 88, North American Vertical Datum of 1988.



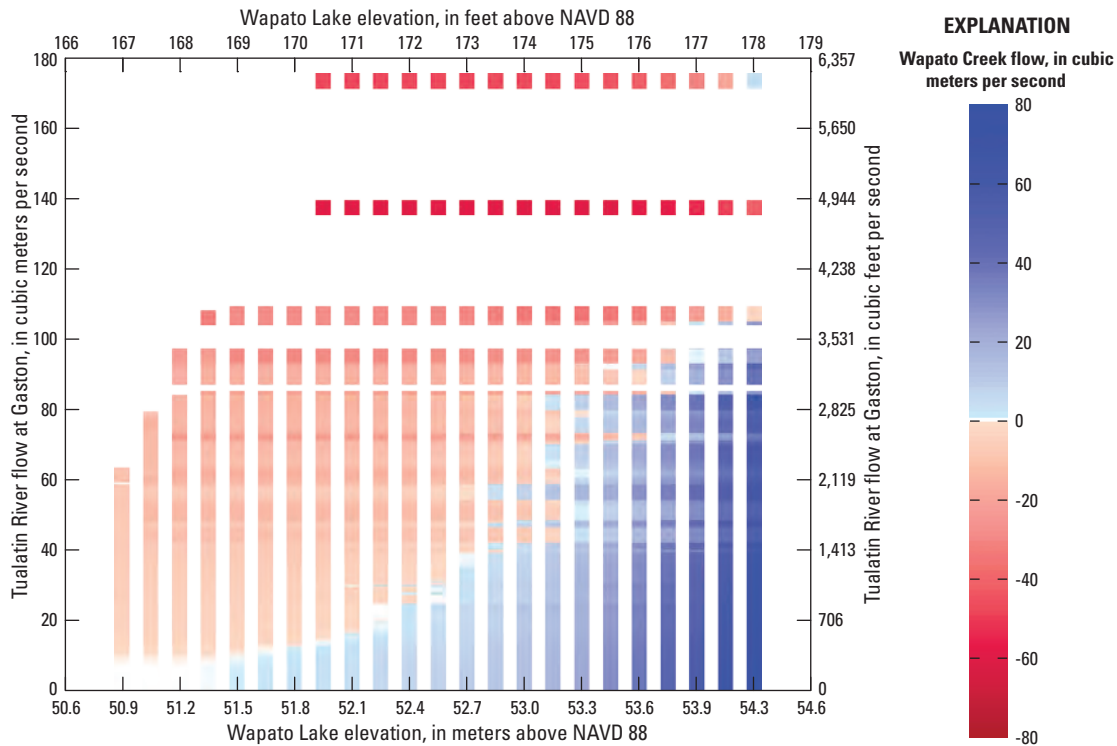
**Figure 7.** Comparison of modeled and measured water levels in Wapato Creek at Gaston Road, northwestern Oregon (U.S. Geological Survey station 14202650), for the November 2011 to April 2013 validation period. HEC-RAS, Hydrologic Engineering Center-River Analysis System; NAVD 88, North American Vertical Datum of 1988.

0.16 m (0.52 ft) and a mean error of 0.065 m (0.21 ft). Despite the inclusion of eight large storms with high water levels, as well as relatively rapid declines in water level between those storms, the model captured the timing and magnitude of water-level variations during November 2011–April 2013. The model did not reproduce subtle variations in measured base-flow water levels during summer 2012. Summertime water levels were known to be affected by factors whose variability was not included in the model, such as the periodic installation of flash boards downstream of the water-level measurement site and periodic dam-building activities of beavers and resulting changes in the height and rate of leakage through their dam. It was beyond the scope of this work to fully capture those variations in base flow in Wapato Creek, and the resulting model likely would have been over-calibrated and therefore less able to respond accurately to future changes in hydrologic conditions. The model was based on accurate bathymetric data and reliable streamflow measurements at the boundary conditions, and it reproduced patterns in the data with sufficient accuracy for the ultimate purpose of supporting the Wapato Lake water budget and its use for evaluating water-management strategies. Therefore, the model was deemed suitable for further integration with the WMST and the population of lake/creek exchange flows for that water-budget tool, with the understanding that model modifications might be required if Wapato Creek channel characteristics are altered in the future.

## Lake/Creek Flow-Exchange Rates

The calibrated HEC-RAS model was used to simulate daily streamflow in Wapato Creek at Gaston Road in response to measured conditions in the Tualatin River during water years 1992–2014. Synthetic statistical water years (10th, 25th, 50th, 75th, and 90th percentiles) also were simulated. For each of these 23 water years and 5 statistical years, the HEC-RAS model was run with a constant upstream water level on Wapato Creek to simulate a hypothetical lake level on an open connection between the lake and creek. Twenty-three different lake levels were imposed, resulting in a range of predicted lake/creek flow-exchange rates (fig. 8). The pattern in the predicted flow-exchange rates is easy to understand, with higher flows discharged from the lake when lake levels are high and downstream river flows are low, and reverse flows when river streamflows are high and lake levels are low. These results were tabulated by lake level and date, producing a lookup table that was imported into the WMST, thus allowing lake/creek flow-exchange rates for an open-outlet condition to be estimated from a range of pre-computed conditions. The date was essentially a surrogate for river conditions that occurred at that time; thus, lake level and river flow (by the date) were indices for the lookup table.

The lookup tables generated from HEC-RAS model results covered a range of lake levels from 50.9 to 54.3 m (167 to 178 ft) at intervals of 0.15 m (0.5 ft), but potential lake levels ranged from a low of 49.4 m (162 ft) when the lake is empty to a high of 56.1 m (184 ft), at which point the lake



**Figure 8.** Flow-exchange rates between Wapato Lake and Wapato Creek, northwestern Oregon, simulated by the Hydrologic Engineering Center-River Analysis System (HEC-RAS) model for water years 1992–2014. Wapato Creek at Gaston Road streamflow is shown as a function of Wapato Lake water level and Tualatin River streamflow at Gaston, Oregon. Negative Wapato Creek flows (in shades of red) represent a reversed flow direction, with water flowing upstream and into the lake due to high water downstream. NAVD 88, North American Vertical Datum of 1988.

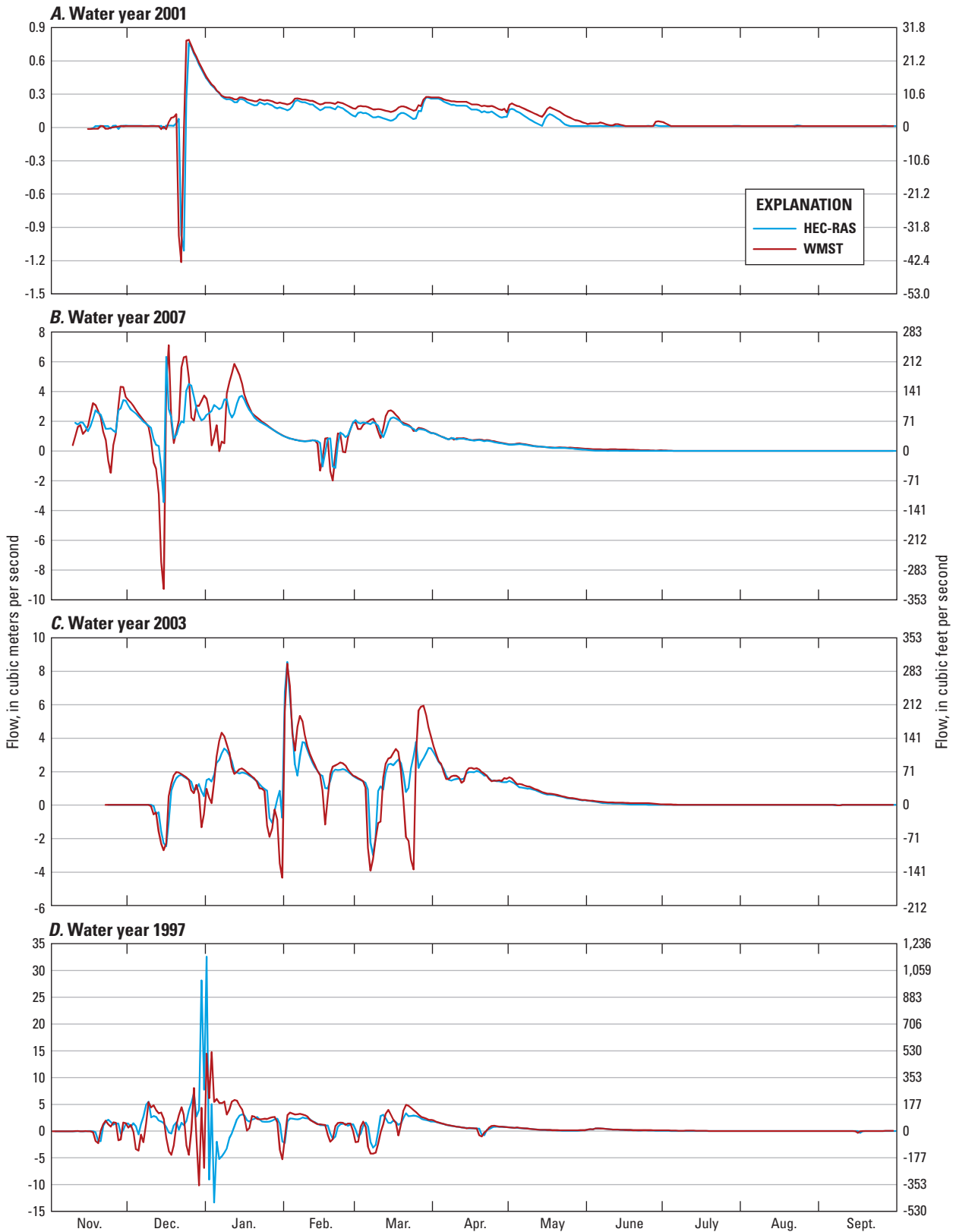
would begin to overflow its levees. HEC-RAS model results essentially converged at the low end of simulated lake levels, with results nearly identical at the two lowest simulated lake levels. Outflows in the lookup table were set to zero at and below a lake level of 50.1 m (164.5 ft), which was roughly the elevation of the bottom of Wapato Creek near Gaston Road. Flow-exchange rates between lake levels of 50.3 m (165 ft) and 50.7 m (166.5 ft) in the lookup table were set identical to the rates at 50.9 m (167 ft). If negative flow-exchange rates at that lake level were less than or equal to  $-0.03 \text{ m}^3/\text{s}$  ( $-1 \text{ ft}^3/\text{s}$ ), then that rate was imposed on all lake levels less than that level. Exchange rates at lake levels greater than 54.3 m (178 ft) were set to those resulting from that maximum simulated lake level. The lookup table in the WMST was populated at lake-level intervals of 0.15 m (0.5 ft); an interpolated exchange rate was computed in the WMST by finding the exchange rates for the nearest two lake levels (above and below), and calculating a linear interpolation between the two rates based on the current lake level.

## Verification of WMST Predictions

To verify that results from the open-outlet-enabled WMST closely followed those calculated directly by the HEC-RAS unsteady flow model, the WMST lake water budget

and the HEC-RAS model were run under identical river flow and lake-level conditions to compare flow outputs at the lake outlet. In short, the WMST simulated a daily water budget for selected water years with an open lake outlet, using the open-outlet flow-exchange rate table generated previously by the HEC-RAS model. A time-series of daily lake levels predicted by the WMST then was imposed as the upstream water-level boundary condition on Wapato Creek for the HEC-RAS model for those same years. Four water years were tested: a dry year (2001), an average rainfall year (2007), a wet winter year (2003), and a wetter year with a large storm (1997). The WMST was run with an initial lake level of 50.6 m (166 ft), an open outlet year-round, and routing the three largest tributaries (Ayers, Wapato, and Hill Creeks) into the lake. An option to limit evapotranspiration in the WMST water budget based on the unsaturated zone's water content was turned on. The initial lake level and rerouted tributaries were chosen in an attempt to reflect potential refuge-management goals, and also to minimize instabilities in the HEC-RAS model that occurred when lake level was less than 50.9 m (167 ft).

WMST lake outflow rates were compared to simulated HEC-RAS streamflows in Wapato Creek at the Gaston Road station (HEC-RAS river mile 1.85 cross section) for each of the water years tested (fig. 9). For the low-flow year (2001, fig. 9A), exchange rates were relatively small



**Figure 9.** Streamflow from the Hydrologic Engineering Center-River Analysis System (HEC-RAS) model and from the Wapato Lake Water Management Scenario Tool (WMST) under a wide range of hydrologic conditions in Wapato Creek at Gaston Road, northwestern Oregon, in water years (A) 2001, (B) 2007, (C) 2003, and (D) 1997. Positive flows are downstream (out of the lake) and negative flows are upstream (into the lake).

(less than 1.2 m<sup>3</sup>/s [42 ft<sup>3</sup>/s]) and characterized by a single notable storm in late December. The typical pattern during many such storms was for water levels in the Tualatin River to rise more quickly than water levels in the Wapato Creek drainage, causing streamflow to reverse in Wapato Creek during the early part of the storm as Tualatin River water backed up in the creek. Shortly thereafter, Wapato Creek water levels increased in response to storm runoff upstream and the direction of flow was restored to the downstream direction. These relatively low exchange rates from the WMST and HEC-RAS in 2001 were similar in their timing and magnitude, providing some validation of the accuracy of open-outlet results from the WMST for a low-flow year. For average rainfall (2007, [fig. 9B](#)) and wet winter (2003, [fig. 9C](#)) conditions, streamflow patterns from the WMST and HEC-RAS matched well in terms of timing and magnitude, but WMST flows tended to have a higher magnitude during times of flow reversals, with larger negative and positive flows. Outside of a few discrepancies, results from the WMST and HEC-RAS agreed well during medium and small storms as well as base-flow conditions.

During a winter with a large storm and high river levels in late December and early January (1997, [fig. 9D](#)), greater discrepancies between WMST and HEC-RAS streamflows occurred in terms of timing and magnitude. Regardless of the cause of these timing issues, the total volume exchanged between lake and creek evened out after the storm, with cumulative streamflow volumes from the two models that were within about 1 percent by the end of the water year ([fig. 10](#)). The Wapato Lake WMST is meant to be used for the evaluation of water-management strategies as opposed to real-time water management during large storms; therefore, these results indicate that the approach of using a lookup table of flow-exchange rates in the WMST to represent lake/creek outflows, as generated from a series of HEC-RAS model runs, is a valid approach and accurate enough to use in WMST water-budget scenarios for an open lake outlet.

## Water-Management Scenarios

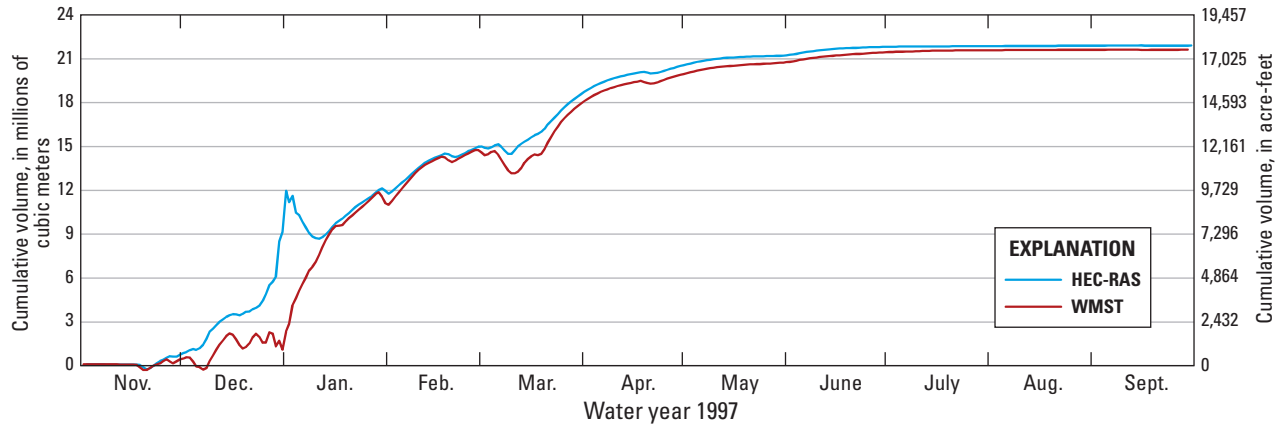
Two water-management scenarios were explored with the WMST to illustrate how an open lake outlet might affect the Wapato Lake water budget and resulting lake levels, and to show how that information might be used to evaluate potential restoration scenarios for Wapato Lake. The objective was to evaluate how an open outlet might affect the management of water levels and the amount of shallow and deep water that could be critical in determining available habitat for target species in the lake. In these scenarios, all the tributaries were routed around the outside of the lakebed, similar to how they have been treated for years, but the pumphouse at the historical outlet of the lake was removed to create an open connection between Wapato Lake and Wapato Creek downstream. In scenario 1, the lake outlet remained open year-round. In scenario 2, a gate was used to close that outlet during the time of highest downstream water levels (mid-November to

mid-April). Although several water years were evaluated, water year 2012 was chosen as an example because that winter had about a half-dozen distinctly separated and moderate storms that provided a good illustration of how river and lake levels would respond to an open outlet. A summary of the water-management details for these scenarios is given in [table 1](#).

### Scenario 1—Open Outlet Year-Round

With a lake outlet open year-round, water could enter or leave the lake through that outlet at any time in response to changes in water levels in the lake and downstream. During water year 2012, a series of distinct and separate storms increased water levels in the Tualatin River downstream and in Wapato Creek, causing the WMST to predict large volumes of water being imported into the lake through the open connection. When water levels downstream receded after each storm, some of that imported water was exported and lake levels decreased ([fig. 11](#)). At their peak in mid-March, lake levels were 2.5 m (8.1 ft) deeper than they were at the start of the water year, and lake levels slowly receded as the wet winter season gave way to dry summer conditions. Overall, the lake's water budget was dominated by inflows and outflows through the open outlet, with 81 percent of all water inputs and 86 percent of all water losses from the lake flowing through the open outlet ([fig. 12](#)). The only other substantial input was precipitation (18 percent), and the only other substantial loss process was open-water evaporation (12 percent).

A major factor in the availability and quality of habitat for waterbirds is water depth, with research showing that many wading birds, shorebirds, and dabbling duck species favor shallow water, whereas diving birds favor deeper water (Colwell and Taft, 2000). Optimal water depths for a managed lake/wetland complex depend on the habitat requirements of the target species, which may vary over the course of a year. For any day in its water-budget computations, the WMST calculated the area of the lakebed divided among several user-defined water-depth categories. Because the desired depth ranges required to support a range of target species vary, depth ranges of 0–1 m (0–3.3 ft), 1–2 m (3.3–6.6 ft), and more than 2 m (6.6 ft) were used as simple categories that encompass shallow, moderate-depth, and deep-water conditions. For lake levels that resulted from a year-round open outlet in scenario 1, deep-water conditions dominated the lake for 1 to several weeks at a time during the largest storms of winter ([fig. 13](#)). Moderate depths characterized most of the lake most of the time from late November through July, and shallow-water conditions dominated only prior to the start of the wet season and late in the summer. At other times, shallow water was fragmented and limited to narrow margins around the edge of the lake.

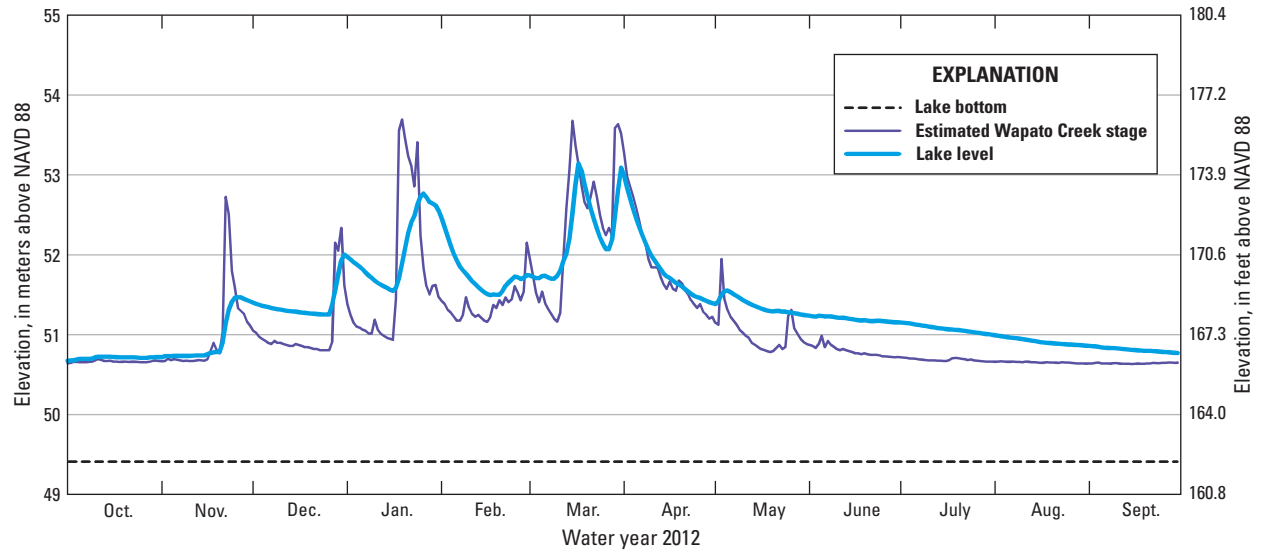


**Figure 10.** Cumulative streamflow volume from the Hydrologic Engineering Center-River Analysis System (HEC-RAS) model and from the Wapato Lake Water Management Scenario Tool (WMST) in Wapato Creek at Gaston Road, northwestern Oregon, during water year 1997 under conditions of an open connection between Wapato Lake and Wapato Creek.

**Table 1.** Hypothetical scenarios tested with an open lake outlet in the Water Management Scenario Tool (WMST) for Wapato Lake near Gaston, northwestern Oregon.

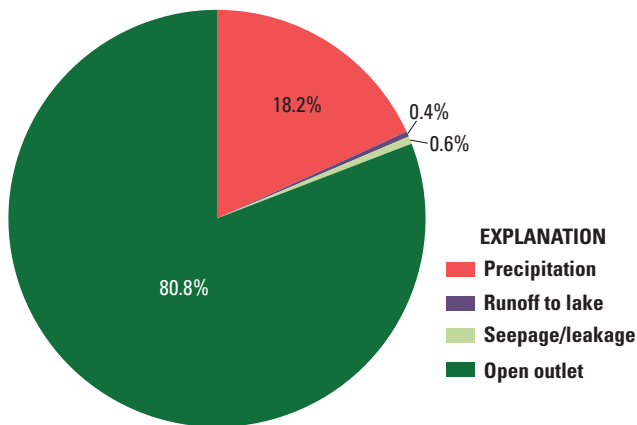
[Symbol: —, option not used]

Input category	Details	Scenario 1 (open)	Scenario 2 (open/closed)
Initial level	Set the lake's initial water-level elevation on October 1 to 50.67 meters (166.25 feet).	X	X
Hydrology	Test a range of hydrologic and meteorological conditions (water years 1992–2014), but use conditions from water year 2012 for illustration purposes as a “typical” year.	X	X
Evapotranspiration	Activate the option to limit evapotranspiration based on the unsaturated zone's water content.	X	X
Tributaries	Divert all tributaries around the lake.	X	X
Pumps	Do not use pumps to manage water levels.	X	X
Lake outlet	Open the lake outlet year-round.	X	—
	Open the lake outlet, but close it during periods (November 15 through April 15) when high-water conditions occur downstream.	—	X

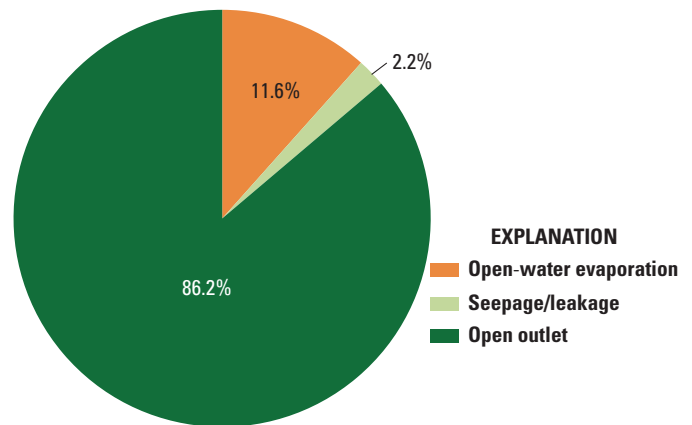


**Figure 11.** Predicted water levels for Wapato Lake near Gaston, northwestern Oregon, using flow and meteorological conditions from water year 2012 and a year-round open connection (scenario 1) between Wapato Lake and Wapato Creek and the Tualatin River. NAVD 88, North American Vertical Datum of 1988.

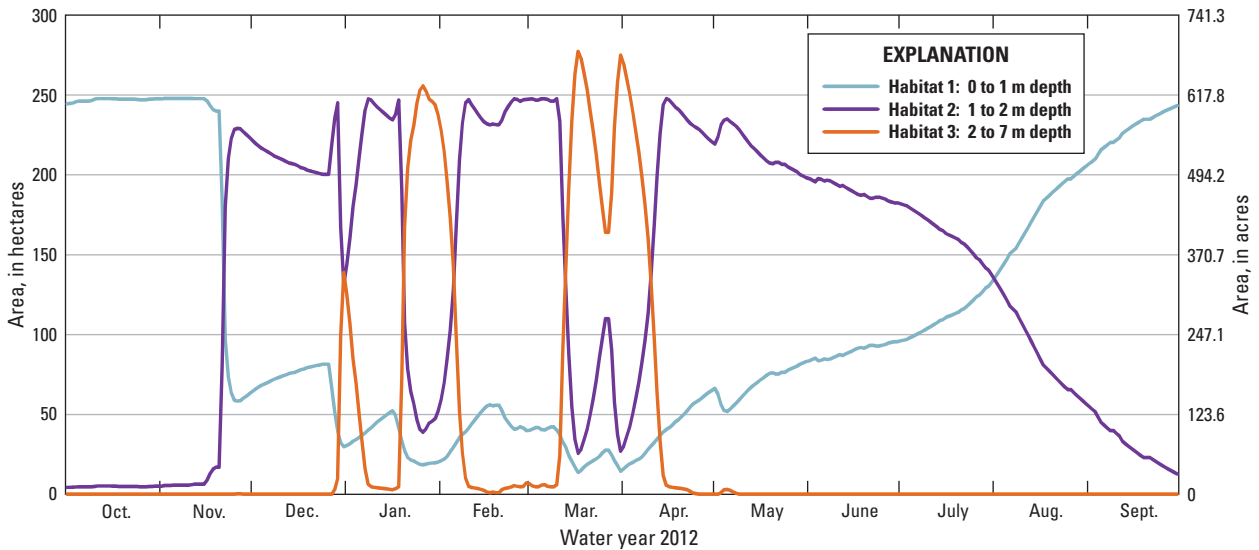
#### A. Water inputs



#### B. Water losses



**Figure 12.** Percentages of total water (A) inputs to and (B) losses from Wapato Lake near Gaston, northwestern Oregon, as computed from the daily lake water budget for a year-round open lake outlet (scenario 1) and using flow and meteorological conditions from water year 2012. Total inputs were 18.2 million cubic meters ( $m^3$ ) (14,800 acre-feet). Total losses were 18.5 million  $m^3$  (15,000 acre-feet).



**Figure 13.** Potential habitat areas associated with three water-depth ranges, as predicted with a year-round open lake outlet (scenario 1) for Wapato Lake near Gaston, northwestern Oregon, using flow and meteorological conditions from water year 2012.

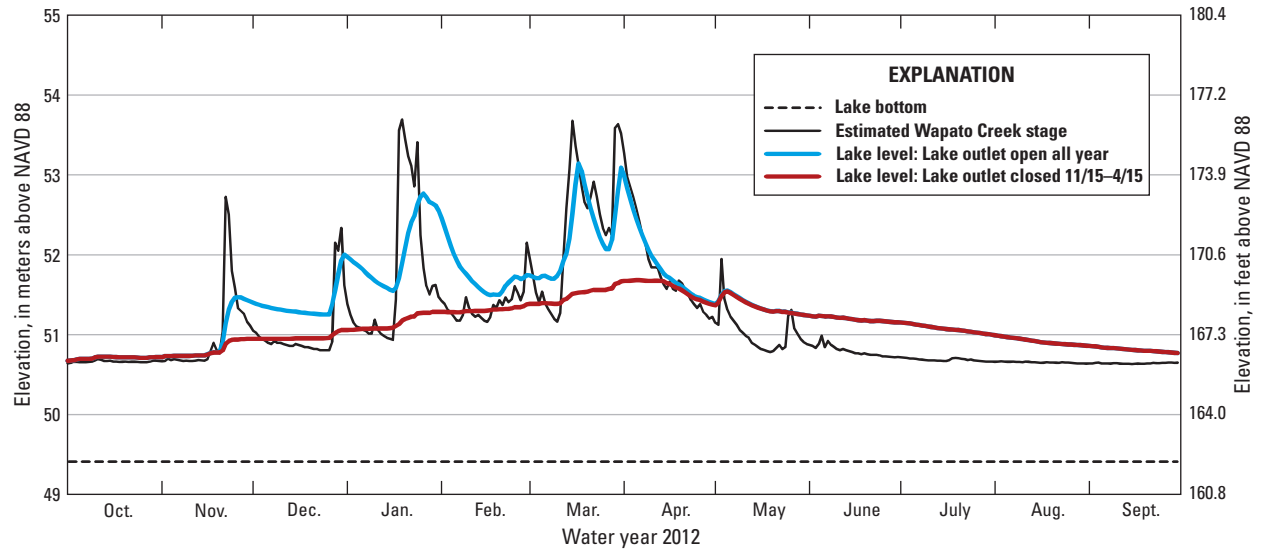
## Scenario 2—Open Outlet Scheduled

Although some advantages, such as a greater capacity for temporary floodwater storage, might be realized by having the lake's outlet open year-round, the deeper lake water that results during winter storms might not provide the water depths that refuge managers are seeking to create and maintain to benefit various aquatic plants and animals. As an alternative that might also have low maintenance costs, an open connection could be combined with a gate structure at the lake outlet, thus allowing the outlet to be closed temporarily during storms or during part of winter to prevent the import of excess floodwaters. In scenario 2, the lake outlet was kept open except for a period of storms and high water from November 15 to April 15.

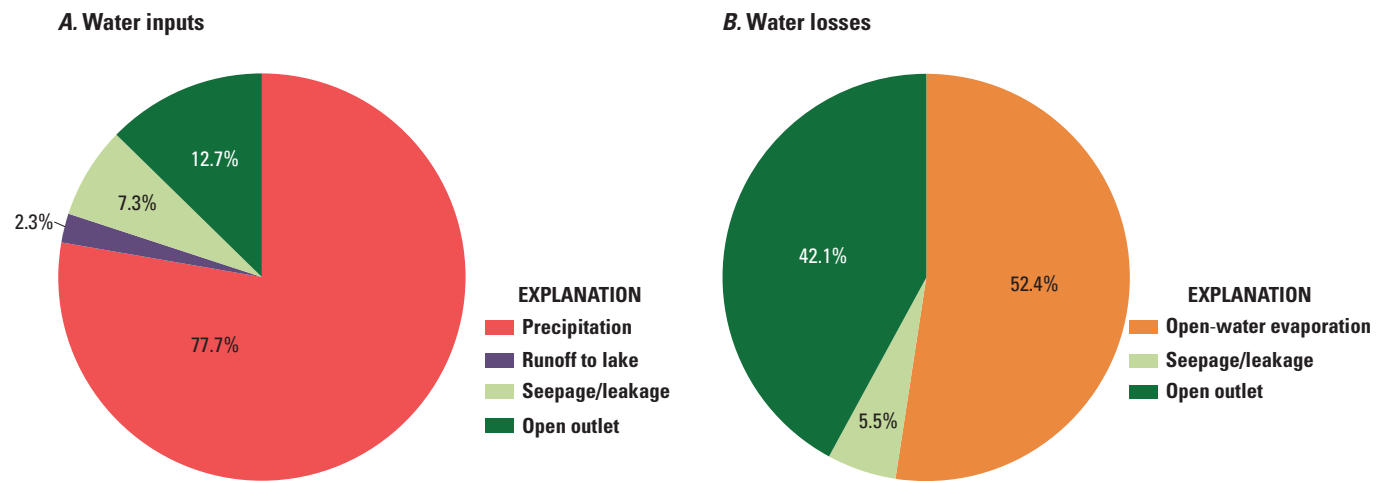
Closing the lake outlet from November 15 to April 15 for conditions that occurred in water year 2012 decreased water inputs through the lake outlet by 96 percent relative to an open outlet year-round. Because the lake outlet was closed during the largest storms and the highest downstream water levels,

the lake level was controlled mainly by an accumulation of rainwater. At a peak in early April, lake levels in scenario 2 were only 1.0 m (3.3 ft) deeper than they were at the start of the water year, a full 1.5 m (4.8 ft) decrease from scenario 1 (fig. 14). In scenario 2, precipitation accounted for 78 percent of the lake's water inputs, with the open outlet accounting for only 13 percent of water inputs (fig. 15). Water losses were dominated by open-water evaporation (52 percent) and exports through the open outlet (42 percent).

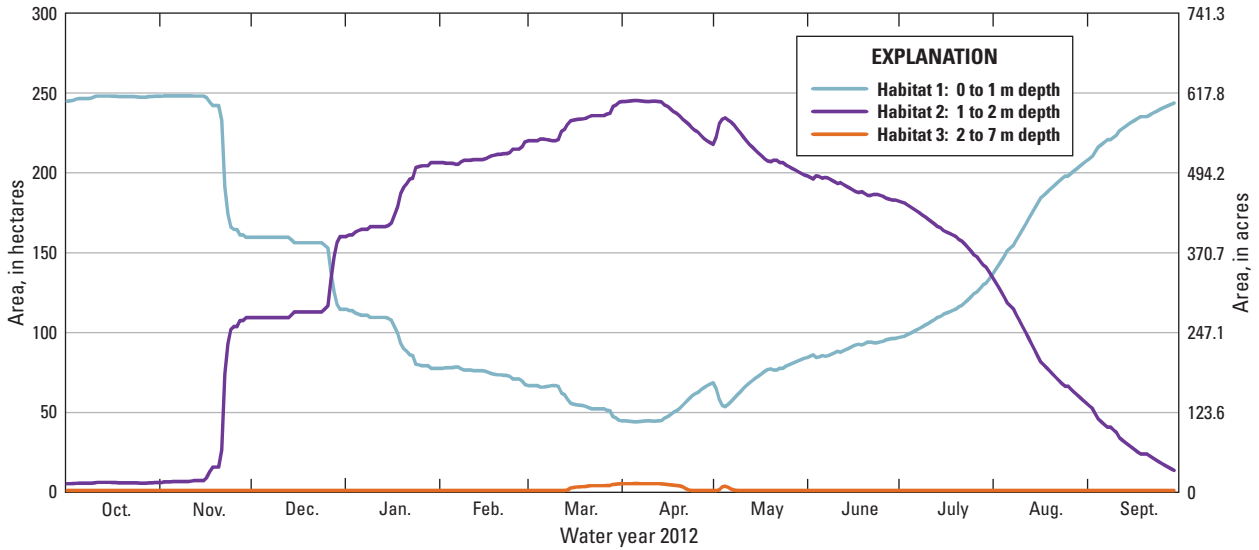
By keeping lake levels lower, water depths greater than 2 m (6.6 ft) were virtually eliminated, and a greater amount of shallow water was retained throughout the year in scenario 2 (fig. 16). Shallow-water conditions in winter would still be limited to the margins of the lake because the lake bottom is relatively flat, and the area of shallow water was largely unchanged from scenario 1 to scenario 2 for the time frame outside November 15–April 15. When the lake outlet was closed, however, water less than 1 m (3.3 ft) in depth was predicted to cover about 50 hectares (124 acres) more than in scenario 1.



**Figure 14.** Predicted water levels for Wapato Lake near Gaston, northwestern Oregon, using flow and meteorological conditions from water year 2012 and year-round open connection (scenario 1) as well as an open connection between Wapato Lake and Wapato Creek and the Tualatin River that is closed during part (November 15 to April 15) of the wet winter season (scenario 2). NAVD 88, North American Vertical Datum of 1988.



**Figure 15.** Percentages of total water (A) inputs to and (B) losses from Wapato Lake near Gaston, northwestern Oregon, as computed from the daily lake water budget for scenario 2, in which the lake outlet was closed during November 15–April 15, and using flow and meteorological conditions from water year 2012. Total inputs were 4.1 million cubic meters ( $\text{m}^3$ ) (3,300 acre-feet). Total losses were 4.1 million  $\text{m}^3$  (3,300 acre-feet).



**Figure 16.** Potential habitat areas associated with three water-depth ranges for Wapato Lake near Gaston, northwestern Oregon, as predicted for scenario 2, in which the lake outlet was closed during November 15–April 15, and using flow and meteorological conditions from water year 2012.

## Implications for Restoration and Water Management

### HEC-RAS Flow Modeling

The calibrated HEC-RAS model reproduced patterns in streamflow and flow direction in Wapato Creek in response to storms and downstream Tualatin River conditions. A characteristic flow reversal often was measured at the beginning of storms in Wapato Creek at Gaston Road (USGS station 14202650), with water in the creek temporarily flowing upstream because of a rapid increase in downstream water levels, followed by a return to a normal flow direction as runoff in the Wapato Creek drainage accumulated and moved downstream (fig. 9). This dependence of flow magnitude and direction on upstream water level (tributary conditions or lake level) and downstream flow condition was critical to capture and incorporate in the WMST water-budget tool.

HEC-RAS was used to simulate lake/creek exchange flows to populate a lookup table for the WMST based only on lake level and date, using the date as a surrogate for downstream river flow and related antecedent conditions, but the lake level in each of the HEC-RAS model runs was constant. It was important, therefore, to determine whether the daily exchange flows used by the WMST were sufficiently accurate to capture the general timing, variability, and magnitude of lake/creek flow-exchange rates under a dynamically changing lake-level scenario. Using a WMST-generated time-series of daily lake levels as an upstream boundary condition on Wapato Creek, the HEC-RAS model was run to compare the magnitude and timing of the lake/creek exchange rates from the two models (fig. 9). The general magnitude of the

exchange flows was expected to be similar because the ultimate source of those flows was from the HEC-RAS model, but it was unknown whether the WMST would capture the timing and variability of the dynamic exchange flows without an iterative solution technique. Agreement between WMST-generated lake outflows and HEC-RAS simulated flows was good for base-flow conditions and small to moderate storms, but large storms sometimes showed some lack of agreement in the timing, magnitude, and direction of flow response (fig. 9D). Some overshoot and a bit of oscillation in the storm-associated exchange rates was obvious in the results, but the comparison showed no systematic timing or lag problems. In addition, despite the presence of some disagreement in the two models at time scales of 1 or 2 days, the overall volume of water moving in or out of the lake was predicted to be similar from both the WMST and HEC-RAS for time frames longer than individual storms (fig. 10).

Tualatin River flows and Wapato Lake levels seemed to be the most important factors accounting for flow and flow direction in Wapato Creek, but other factors in the HEC-RAS model had minor effects. The flow from Scoggins Creek, a tributary that enters the Tualatin River downstream of the Wapato Creek confluence, was one such factor. When flow in Scoggins Creek was high, that additional water provided some resistance to downstream Tualatin River flow, and thus increased the downstream resistance to Wapato Creek flows entering the Tualatin River. Scoggins Creek is a large and important tributary, with flows that can reach more than 30 m<sup>3</sup>/s (1,060 ft<sup>3</sup>/s) and account for a substantial fraction of the total flow in the Tualatin River. Farther downstream, HEC-RAS results showed that the Spring Hill Road bridge structure

at the downstream Dilley boundary also provided some resistance to downstream Tualatin River flows, contributing to high water levels when Tualatin River flows were high.

In Wapato Creek, the HEC-RAS model was particularly sensitive to creek bathymetry and to a beaver dam that was included in the model. About 0.50 km (0.31 mi) downstream from Gaston Road, the highest bottom elevation of the creek was roughly 50.4 m (165.3 ft), which was one factor restricting lake/creek water exchange when lake levels were low. The other factor was the beaver dam at a location 1.1 km (0.69 mi) downstream from Gaston Road, modeled as a “leaky” structure with a top elevation of 51.2 m (168.1 ft) and allowing 0.014 m<sup>3</sup>/s (0.5 ft<sup>3</sup>/s) of flow to pass through when water levels were below its crest. The HEC-RAS model was used to simulate flows in Wapato Creek at lake levels from 50.9 to 54.3 m (167–178 ft), but Wapato Lake levels can decline below that range. Largely because of the beaver dam and the elevation of the creek bottom, simulated flows in Wapato Creek decreased greatly and converged at a lake elevation of 50.9 m (167 ft), with modeled flows essentially the same at that level as at 51.1 m (167.5 ft). The effect of the beaver dam was apparent during model calibration/validation, with simulated water levels at Gaston Road remaining constant at a minimum lake elevation of 51.3 m (168.2 ft) during summer 2012 low-flow conditions (fig. 7), only slightly higher than the crest elevation of the beaver dam downstream.

## Uncertainties and Sources of Error

Although the calibrated HEC-RAS model reproduced patterns in streamflow measurements with acceptable accuracy, application of such models is best done with a knowledge of model uncertainties and any sources of potential error. Accurate HEC-RAS models are built upon plentiful and representative channel and floodplain cross-sectional information and accurate boundary conditions. In this case, the lower reaches of Scoggins Creek were not surveyed because access to the land could not be obtained; therefore, that creek was modeled only as a tributary input even though its channel crossed the Tualatin River floodplain in the model reach. On Wapato Creek, a relatively large number of cross sections was surveyed, but those cross sections may not have contained an optimal number of points in the narrow active channel, perhaps resulting in some mischaracterization of the channel shape or its deepest point. In addition, more bank surveying would have helped to resolve uncertainties stemming from potential vegetation bias in the “bare-earth” lidar data that were used to help construct model cross sections.

Continuous streamflow data always have uncertainty, and some of the flow data used in the model were estimated. Streamflow data from the Tualatin River at Gaston (OWRD station 14202510) were collected by OWRD and presumed to have an accuracy rating of “good” because previous data collected by USGS at the same site had that rating; such a rating

implies an uncertainty of about 10 percent. Streamflow data from Dilley (USGS station 14203500) also were rated “good” for the model calibration and validation period. Flows at both stations on the Tualatin River (Gaston, Dilley) included overbank conditions where excess flow moved to side channels and the floodplain. Streamflow rates under such conditions were estimated for the Gaston station using a water-balance method; at the downstream Dilley station, those overbank flows were measured and included by USGS in the published data. The Scoggins Creek streamflow data had similar uncertainties, but those flows tended to be less variable because of reservoir regulation.

Some additional model error may be traced to inaccuracies in the representation of instream structures (bridges, beaver dams), generalizations in frictional roughness factors, and the need to keep the model’s response general. To meet the objectives of the study, the model needed to reproduce the timing, patterns, and magnitude of flows and water levels under a variety of flow conditions and over a period of many years. Model parameters can be fine-tuned to optimally fit the response to specific storms, but over-calibration to fit every detail likely would not maintain fidelity to measurements across a wider range of storms, climate conditions, and vegetation cycles. Some amount of model error, therefore, was expected based on uncertainties in the data and model configuration, and was deemed acceptable for any single storm because the general response across a wider range of conditions was reproduced well.

## Accuracy of Flow-Exchange Rates

Lake/creek flow-exchange rates predicted by HEC-RAS and the WMST showed good agreement under most of the conditions tested (fig. 9). The WMST overpredicted the exchange rate during storms, sometimes predicting a larger negative flow rate at the beginning of a storm compared to HEC-RAS results, followed by a larger positive flow rate later in the storm. Part of this discrepancy occurred because the WMST computed the lake water balance on a daily basis, whereas HEC-RAS was run with a 15-minute time step. Typically, these errors decrease over subsequent time intervals and the two models generally agreed on the cumulative volume of water moving in or out of the lake (fig. 10). During large multi-day storms with some of the highest streamflows in this study (December 1996–January 1997), predicted flow-exchange rates from the two models were not in good agreement (fig. 9D). These rare and large winter storms typically do not affect water levels or potential habitat for target species during summer, and are not expected to skew lake water-budget predictions later in the water year. The discrepancy in results during such large storms serves as a good reminder that it is best to focus not on individual storm conditions, but rather on longer-term patterns in water levels and habitat.

## Insights from WMST Scenarios

With the addition of an open lake-outlet option in the Wapato Lake WMST, resource managers have a tool to explore a wide range of potential options for restoration and lake-level management. The WMST predicts daily water levels and depth-related habitat areas over the course of a chosen water year and in response to user settings for pumping, tributary flow routing, and outlet options. In the two scenarios highlighted in this report, a hypothetical restored outlet of Wapato Lake was opened year-round (scenario 1) or opened most of the year (scenario 2, [table 1](#)). Pumps were not used to try to control the lake level and all tributaries were routed around the lake. As a result, flows in and out of the lake's outlet dominated the lake's water budget in scenario 1 ([fig. 12](#)), with most of that water moving in and out of the lake during winter. Closing the lake's outlet for most of the winter in scenario 2 kept water levels in the lake shallower and greatly reduced the total volume of water conveyed through the lake outlet ([figs. 14–15](#)).

Scenario 1 caused most of the lake to become relatively deep ( $> 2$  m [ $> 6.6$  ft]) during large winter storms in the example water year (2012) and caused most of the lake to be deeper than 1 m (3.3 ft) for the entire rainy season and well into mid-summer ([fig. 13](#)). These relatively deep waters could be unsuitable for waterbird species that require shallow-water habitat. In addition, deep water in the early part of summer could retard the growth of, or prevent the establishment of, native plant communities that could be critical to the future restoration of Wapato Lake. In that case, one way to keep water levels lower and avoid some of the maintenance and operational costs associated with pumps would be to close the lake outlet for part of the winter, as in scenario 2. In that scenario, the lake outlet was closed for 5 months, but the choice of when to close the lake outlet in any given year would depend on downstream flows and water levels relative to target lake levels and the habitat requirements of target species.

Optimal water depths in Wapato Lake will depend on the habitat requirements of the fish and wildlife species of greatest interest. Research has shown that water depth is an important factor in determining usage by different species of waterbirds, with shallow-water habitats favoring a wide diversity of wading birds, shorebirds, and dabbling duck species; and deeper water favoring diving ducks and coots, for example (Murkin and others, 1997; Colwell and Taft, 2000; Taft and others, 2002). Wapato Lake has been an important resource for hundreds of tundra swans (*Cygnus columbianus*) as well as mallards (*Anas platyrhynchos*), northern pintails (*Anas acuta*), canvasbacks (*Aythya valisineria*), ring-necked ducks (*Aythya collaris*), and Canada geese (*Branta canadensis*), along with various species of shorebirds (U.S. Fish and Wildlife Service, 2007). When Wapato Lake has deep water, the shape of the lakebed dictates that shallow water is limited to small areas around the margin of the lake; such shallow areas might have been more extensive historically when the lakebed was not

constrained by levees. To continue to support a variety of waterbirds requiring a range of water depths, USFWS may wish to avoid creating some of the deeper depths resulting from the year-round open outlet in scenario 1. A lake outlet that is closed for part of the winter high-water season would produce lower lake levels and more shallow-water areas in the lake.

In the scenarios of this study, Wapato Creek was connected to a hypothetical restored outlet of Wapato Lake and all flows in Wapato Creek immediately downstream of the lake resulted from flows moving through that outlet. If any Wapato Lake tributaries were reconnected to the lake, those inputs would directly contribute to the lake's water budget and most of that water eventually would leave the lake through the lake's outlet. Any tributaries not reconnected to the lake were assumed to be routed elsewhere, perhaps directly to the Tualatin River through a connection near Gaston, or perhaps to Wapato Creek farther downstream, such that the extra flow from the tributaries was assumed to not greatly affect Tualatin River flows or Wapato Creek water levels. If these externally routed tributary waters were to join Wapato Creek near the lake outlet, then they would affect the lake/creek flow-exchange rates, such that the rates in the WMST lookup table would no longer be valid. If such a water-management choice is made in the future, the HEC-RAS model would need to be re-run under those conditions to better simulate the lake/creek flow-exchange rates.

If all of Wapato Lake's tributaries were to be routed into the lakebed, predicted lake levels with an open lake outlet would be higher than those in the example scenarios. For a year-round open outlet, routing all tributaries into the lake would result in an average increase in water depth of 0.25 m (0.83 ft) during November–May. If diverse water depths and some meaningful amount of shallow-water waterbird habitat is desired, then routing all tributaries into the lakebed under such conditions might not achieve the desired goals.

Results from this study show that opening the outlet of Wapato Lake would not allow the lake to drain by gravity flow below a lake level of about 51.2 m (168.1 ft), mainly because of the elevation of the bed of Wapato Creek and the presence of a beaver dam in that creek downstream of Gaston Road. Predicted lake levels in scenarios 1 and 2 during May–July are higher with these flow restrictions in place than without them. If these obstacles were to be removed or modified, perhaps a scenario with an open lake outlet could achieve more shallow-water areas earlier in the summer season, which could benefit the establishment of wetland plants as well as provide habitat for waterbirds that require shallow water. If such obstacles were removed, however, the lake/creek flow-exchange rates would need to be re-modeled with HEC-RAS and a new lookup table imported into the WMST to evaluate the results of that action. For the purposes of exploring potential water-management and restoration scenarios at this time, however, the current lookup tables and modeling approach is sufficient to provide useful insights and results.

## Supplementary Material

The archived HEC-RAS models and copies of the WMST are available from a USGS website at [https://or.water.usgs.gov/proj/wapato\\_lake/](https://or.water.usgs.gov/proj/wapato_lake/). That website also provides links to archived flow and water-quality data at sites in and around the Wapato Lake NWR. All datasets used to run the water-budget calculations in the WMST are included in the WMST spreadsheet and were obtained from archived sources cited in this report.

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## References Cited

- Bancroft, G.T., Gawlik, D.E., and Rutchey, K., 2002, Distribution of wading birds relative to vegetation and water depths in the northern Everglades of Florida, USA: *Waterbirds*, v. 25, no. 3, p. 265–277, accessed July 20, 2019, [https://doi.org/10.1675/1524-4695\(2002\)025\[0265:DOWBRT\]2.0.CO;2](https://doi.org/10.1675/1524-4695(2002)025[0265:DOWBRT]2.0.CO;2).
- Barnes, H.H., Jr., 1967, Roughness characteristics of natural channels: U.S. Geological Survey Water-Supply Paper 1849, 213 p., accessed July 20, 2019, at [https://pubs.usgs.gov/wsp/wsp\\_1849/pdf/wsp\\_1849.pdf](https://pubs.usgs.gov/wsp/wsp_1849/pdf/wsp_1849.pdf).
- Bolduc, F., and Afton, A.D., 2008, Monitoring waterbird abundance in wetlands—The importance of controlling results for variation in water depth: *Ecological Modelling*, v. 216, p. 402–408, accessed July 20, 2019, at <https://doi.org/10.1016/j.ecolmodel.2008.05.007>.
- Cass, P.L., and Miner, J.R., 1993, The historical Tualatin River Basin: Oregon Water Resources Research Institute, Oregon State University Tualatin River Basin Water Resources Management Report Number 7, 59 p. [Also available at: <https://ir.library.oregonstate.edu/concern/defaults/5q47rt00r>.]
- Christy, J.A., 2015, Historical conditions at Wapato Lake—Washington and Yamhill Counties: Oregon, Portland, Oregon Biodiversity Information Center, Institute for Natural Resources, Portland State University, 7 p.
- Chow, V.T., 1959, Open-channel hydraulics: New York, McGraw-Hill Book Company, Inc., 680 p.
- Colwell, M.A., and Taft, O.W., 2000, Waterbird communities in managed wetlands of varying water depth: *Waterbirds*, v. 23, p. 45–55, accessed July 20, 2019, at <https://www.jstor.org/stable/4641109>.
- Elphick, C.S., and Oring, L.W., 1998, Winter management of Californian rice fields for waterbirds: *Journal of Applied Ecology*, v. 35, p. 95–108, accessed July 20, 2019, at <https://doi.org/10.1046/j.1365-2664.1998.00274.x>.
- Fredrickson, L.H., 1991, Strategies for water-level manipulations in moist-soil systems: *Waterfowl Management Handbook*, U.S. Fish and Wildlife Service Leaflet 13-4-6, 8 p., accessed July 20, 2019, at <https://ecos.fws.gov/ServCat/DownloadFile/58461?Reference=57616>.
- Lantz, S.M., Gawlik, D.E., and Cook, M.I., 2011, The effects of water depth and emergent vegetation on foraging success and habitat selection of wading birds in the Everglades: *Waterbirds*, v. 34, p. 439–447, accessed July 20, 2019, at <https://doi.org/10.1675/063.034.0406>.
- Murkin, H.R., Murkin, E.J., and Ball, J.P., 1997, Avian habitat selection and prairie wetland dynamics—A 10-year experiment: *Ecological Applications*, v. 7, p. 1144–1159, accessed July 20, 2019, at [https://doi.org/10.1890/1051-0761\(1997\)007\[1144:AHSAPW\]2.0.CO;2](https://doi.org/10.1890/1051-0761(1997)007[1144:AHSAPW]2.0.CO;2).
- Oregon Water Resources Department, 1992–2004, Annual reports of the Tualatin River Flow Management Technical Committee: Clean Water Services and Oregon Water Resources Department, District 18 Watermaster [variously paged], accessed July 20, 2019, at <https://www.co.washington.or.us/Watermaster/SurfaceWater/tualatin-river-flow-technical-committee-annual-report.cfm>.
- Oregon Water Resources Department, 2015a, Near real time hydrographics data—Tualatin River at Gaston, Oregon: Oregon Water Resources Department web page, accessed July 20, 2019, at [https://apps.wrd.state.or.us/apps/sw/hydro\\_near\\_real\\_time/display\\_hydro\\_graph.aspx?station\\_nbr=14202510](https://apps.wrd.state.or.us/apps/sw/hydro_near_real_time/display_hydro_graph.aspx?station_nbr=14202510).
- Oregon Water Resources Department, 2015b, Near real time hydrographics data—Scoggins Creek below Henry Hagg Lake near Gaston, Oregon: Oregon Water Resources Department web page, accessed July 20, 2019, at [https://apps.wrd.state.or.us/apps/sw/hydro\\_near\\_real\\_time/display\\_hydro\\_graph.aspx?station\\_nbr=14202980](https://apps.wrd.state.or.us/apps/sw/hydro_near_real_time/display_hydro_graph.aspx?station_nbr=14202980).

- Rounds, S.A., Carpenter, K.D., Fesler, K.J., and Dorsey, J.L., 2015, Upstream factors affecting Tualatin River algae—Tracking the 2008 *Anabaena* algae bloom to Wapato Lake, Oregon: U.S. Geological Survey Scientific Investigations Report 2015–5178, 41 p., <https://doi.org/10.3133/sir20155178>.
- Rounds, S.A., Freed, T.Z., Snyder, D.T., Smith, C.D., Doyle, M.C., Holmes, E., Mykut, C., Mayer, T., Stockenberg, E., and Pilson, S.L., 2020, Evaluation of restoration alternatives using water-budget tools for the Wapato Lake National Wildlife Refuge, northwestern Oregon: U.S. Geological Survey Scientific Investigations Report 2020–5013, 26 p. [Also available at <https://doi.org/10.3133/sir20205013>.]
- Taft, O.W., Colwell, M.A., Isola, C.R., and Safran, R.J., 2002, Waterbird responses to experimental drawdown—Implications for the multispecies management of wetland mosaics: *Journal of Applied Ecology*, v. 39, p. 987–1001, accessed July 20, 2019, at <https://doi.org/10.1046/j.1365-2664.2002.00763.x>.
- U.S. Army Corps of Engineers, 2010, HEC-RAS river analysis system user's manual, version 4.1: U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, California, Report CPD-68 [variously paged], accessed July 20, 2019, at [https://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS\\_4.1\\_Users\\_Manual.pdf](https://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS_4.1_Users_Manual.pdf).
- U.S. Army Corps of Engineers, 2011, HEC-GeoRAS GIS tools for support of HEC-RAS using ArcGIS, user's manual, version 4.3.93: U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, Davis, California, Report CPD-83 [variously paged], accessed July 20, 2019, at [https://www.hec.usace.army.mil/software/hec-georas/documentation/HEC-GeoRAS\\_43\\_Users\\_Manual.pdf](https://www.hec.usace.army.mil/software/hec-georas/documentation/HEC-GeoRAS_43_Users_Manual.pdf).
- U.S. Fish and Wildlife Service, 2007, Tualatin River National Wildlife Refuge Wapato Lake Unit addition—Land conservation plan and environmental assessment, Washington and Yamhill Counties, Oregon: U.S. Fish and Wildlife Service [variously paged]. [Also available at <https://www.fws.gov/pacific/planning/main/docs/OR/Wapato/Final%20LCP%20EA/2%20Wapato%20FONSI%20EA%20LCP.pdf>.]
- U.S. Fish and Wildlife Service, 2019, Wapato Lake National Wildlife Refuge—Environmental assessment, Washington and Yamhill Counties, Oregon: U.S. Fish and Wildlife Service, 94 p. plus attachments, accessed March 4, 2020, at [https://www.fws.gov/refuge/Wapato\\_Lake/final\\_restoration\\_EA/](https://www.fws.gov/refuge/Wapato_Lake/final_restoration_EA/).
- U.S. Geological Survey, 2015, Data inventory page for site 14202980—Scoggins Creek below Henry Hagg Lake, near Gaston, Oregon: U.S. Geological Survey web page, accessed July 20, 2019, at [https://waterdata.usgs.gov/nwis/inventory/?site\\_no=14202980](https://waterdata.usgs.gov/nwis/inventory/?site_no=14202980).
- Washington County, 1872, Washington County road records—Establishment of County Road A 143 (Gaston Road), August 1872: Washington County, Oregon.



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